

A Transmittance-Optimized, Point-Focus Fresnel Lens Solar Concentrator

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INTRODUCTION

ENTECH, INC. (a new company which purchased E-Systems Energy Technology Center in October 1983) is currently developing a point-focus Fresnel lens solar concentrator for high-temperature solar thermal energy system applications. The concentrator utilizes a transmittance-optimized, short-focal-length, dome-shaped refractive Fresnel lens as the optical element. This unique, patented (Ref. 1) concentrator combines both excellent optical performance and a large tolerance for manufacturing, deflection, and tracking errors.

Under Jet Propulsion Laboratory (JPL) funding, ENTECH has completed the conceptual design of an 11-meter diameter concentrator which should provide an overall collector solar-to-thermal efficiency of about 70% at an 815°C (1500°F) receiver operating temperature and a 1500X geometric concentration ratio (lens aperture area/receiver aperture area).

In the following paragraphs, a review of the Fresnel concentrator development program will be presented, including a description of the concentrator, a summary of its expected performance, the key features of the lens, a parquet approach to lens manufacturing, a description of a prototype lens panel, the results of optical testing of the prototype lens panel, and a discussion of a practical mass production approach for the lens panels.

CONCENTRATOR DESCRIPTION

The point-focus lens concentrator is shown in Figure 1 and described in Table 1. The optical element is a convex, dome-shaped, acrylic Fresnel lens. The dome consists of ten conical-segment rings, which are each flat in the radial direction and curved in the circumferential direction. The rim angle of the lens (from optical axis to outermost prism) is 45 degrees. Each of the conical-segment rings is about 61 cm wide, with a smooth outer surface and a prismatic inner surface. The lens is made of uv-stabilized acrylic plastic, about 2.4 mm thick. Steel space-frame structure is employed for both the basic concentrator and the pedestal. Reinforced concrete is used for the foundation. The tracking system provides full two-axis sun-tracking and inverted (lens-down) stowage. The Fresnel concentrator will be adaptable to a wide variety of receivers currently under development by JPL and others. The air volume between lens and receiver is enclosed with a thin aluminum conical shroud to minimize dirt and moisture accumulation on the inner surface of the lens. A slight pressurization of this air volume may be desirable for dust infiltration prevention. The total concentrator weight is about 13,000 pounds (13 pounds per square foot of aperture).

CONCENTRATOR PERFORMANCE SUMMARY

The point-focus Fresnel concentrator performance is summarized in Table 2 for two cases of practical importance. The first case corresponds to a high-temperature receiver which would be required for a Brayton or Stirling engine application. For this case, a 1500X geometric concentration ratio is utilized (corresponding to a receiver aperture diameter of 0.28 meter). After treating reflection/absorption losses in the acrylic lens, 90% of the sunlight is transmitted. Of this transmitted sunlight, about 92% is contained within the limited 0.28 meter receiver aperture circle; i.e., 92% is the receiver intercept factor. About 6% of the lens aperture is blocked by structure; thus the blocking/shading factor is 94%. After all of these loss mechanisms are considered, the overall optical efficiency is 78%. Still considering Case I, this 78% optical efficiency for an 11-meter diameter concentrator (aperture area = 95 m²) corresponds to a black-body receiver energy absorption rate of 59 kw (thermal) under a direct insolation of 800 w/m². Assuming an 815°C receiver temperature, the black body thermal radiation loss will be 5 kw (thermal). Thus, the net collector output will be 54 kw (thermal), corresponding to a 71% overall collector efficiency.

For the second case in Table 2, a lower temperature receiver is assumed, corresponding to a Rankine engine application. For this lower temperature, a lower geometric concentration ratio (500X) provides better overall collector performance. After considering the same loss factors described above, the concentrator optical efficiency is 83%, this higher value being attributable to a better receiver intercept factor for the larger receiver aperture diameter (0.49 meter). After subtracting the 2 kw (thermal) black-body radiation loss corresponding to a receiver temperature of 371°C, the net collector output will be 61 kw (thermal), equivalent to an overall collector efficiency of 80%.

KEY LENS FEATURES

The patented ENTECH concentrator is a dome-shaped Fresnel lens with a smooth outer surface and a prismatic inner surface. The lens is a convex, non-spherical-contour lens, in which each prism transmits direct solar rays with equal angles of incidence and excidence, as shown in Figure 2. This incidence/excidence symmetry (also called the minimum deviation condition) provides each prism with the lowest possible reflection losses, and thereby the highest possible transmittance, for that prism's light deviation (turning) angle, as proven rigorously in Reference 1. In addition to maximal transmittance, this minimum-deviation-prism lens also provides a maximal tolerance for lens contour errors (slope errors), an improved tolerance for lens manufacturing errors (prism angular errors and rounded prism peaks), and a smaller solar image size (including finite solar disk angular diameter and chromatic aberration effects), when compared to previous flat and spherical contour lenses. The optical performance superiority of the new lens is fully described in References 2 and 3. Perhaps the most important attribute of the new transmittance-optimized lens is its high slope error tolerance, which allows a substantial relaxation of the support structure stiffness requirements, and thus a significant reduction in weight and cost of the concentrator. Compared to a reflective concentrator (e.g., a 45 degree rim angle parabolic dish), the Fresnel lens concentrator is more than 100 times more tolerant of radial slope errors, as dramatically illustrated in Figure 3.

PARQUET LENS MANUFACTURING APPROACH

One potentially low-cost manufacturing approach for the point-focus lens is the parquet approach of Figure 4. The dome consists of conical segments which are curved in the circumferential direction and straight in the radial direction. This approach allows the acrylic plastic lens material to be made in flat form and mechanically held in the conical geometry in the completed concentrator. The unfolded flat conical segments can be subdivided into a number of identical lens panels. While these panels would ideally utilize prisms running circumferentially along concentric circles, current manufacturing approaches for lens tooling can not achieve these large-radius non-linear prisms. Fortunately, proven manufacturing approaches are available for making linear prismatic tooling. Thus, the lens panel of Figure 4 is configured to approximate the ideal curved-prism geometry by utilizing a parquet of linear prism elements. The two key variables of this parquet lens approach are the element width (w) and the gap width (g) between elements, since the element width causes a focal plane image enlargement and since the gap width causes transmittance losses. Prototype fabrication efforts have proven that the gap width can be maintained at about 0.5 mm. Element width selection is based on optical analyses discussed below.

Optical analyses of the parquet lens concentrator have been completed. These analyses are based upon cone optics; i.e., the theoretical mapping of the conical bundles of radiation which originate at the solar disk, which are incident upon the lens outer surface, and which form elliptical images in the focal plane, as shown in Figure 5. Because of dispersion (chromatic aberration), the solar images of different wavelengths are spread across the focal plane, as shown in Figure 5. For any fixed receiver aperture diameter and any particular prism in the lens, the design wavelength can be selected to minimize the energy missing the receiver aperture, and thus to maximize the intercept factor. The current lens has been tailored for a 1500X design concentration ratio by properly varying the design wavelength for the various prisms comprising the lens.

For the parquet lens approach, the effect of the parquet element on lens focussing is the formation of a linear solar image in the transverse direction of Figure 5, with the total image transverse length being equal to the parquet element width (w) plus the solar disk image width. The computer model treats this parquet element effect and calculates the radiant flux profile in the focal plane by integrating over all contributing portions of the lens (treating the local lens transmittance), and over all contributing wavelengths, to define the total radiant flux concentration at each point in the focal plane. Results of such a flux profile calculation for several parquet element widths are shown in Figure 6. The radiant flux is normalized by the one-sun direct solar flux incident on the lens, while the radial position in the focal plane is normalized by the lens aperture radius, for the results shown in Figure 6. As expected, the larger the parquet element width, the more spread out the image becomes. However, the image spreading effect is small for element widths of 5 inches and less, when one notes that a 1500X geometric concentration ratio corresponds to a receiver normalized radius (P/R) of 26×10^{-3} in Figure 6. The flux profile labeled $W=0$ represents the ideal lens with non-linear prisms.

The flux profiles of Figure 6 can be integrated over various size receiver circles to define the overall energy interception rate for various geometric concentration ratios. The results of such an integration are shown in Figure 7, wherein the intercepted energy rate has been normalized by the energy rate incident on the lens outer surface; thus the effective transmittance (optical efficiency) is shown as a function of geometric concentration ratio for lenses with various parquet element widths. (The results of Figure 7 do not include absorption losses within the thin acrylic lens, which are expected to be 1-2%, based upon measurements for similar acrylic Fresnel lenses. Also, the results in Figure 7 do not include structural blocking/shading losses, although this 6% loss was included in Table 2.) Note that wide parquet element widths work well for low geometric concentration ratios, but not well for high geometric concentration ratios, due to the image spreading effect of the parquet width. Note also that there exists an optimal element width for each value of geometric concentration ratio, this optimum corresponding to the best tradeoff of image spreading losses (which increase with element width) and gap losses (which decrease with element width since g/w represents the lost gap area fraction). For 1500X geometric concentration ratio, element widths of 2, 3, and 4 inches provide essentially equal performance. To minimize lens complexity, the 4-inch element width has been selected for prototype fabrication, as discussed below.

PROTOTYPE LENS PANEL

A prototype lens panel, using the parquet lens manufacturing approach, has been fabricated for optical testing. This panel is described in Table 3. The panel represents one part of the conical ring located between 27.9° and 32.1° of local rim angle, measured from the lens optical axis. This segment was selected for prototype fabrication because its optical performance is typical of the full dome lens performance. A nominal 2 foot by 4 foot panel size was selected for prototype fabrication, using 12 linear prismatic parquet elements of 4 inch average element width (w) to form the 4 foot curved dimension of the panel. The linear prismatic elements were made by 3M Corporation to ENTECH's specification, using 3M's low-cost lensfilm process. The twelve elements were solvent-bonded to a single piece of extruded acrylic sheet to form the final panel. The entire laminated panel thickness is about 0.1 inch.

LENS PANEL OPTICAL TESTING

Optical performance testing of the prototype lens panel has been successfully completed. The panel and a focal-plane radiant flux measurement system were mounted on a two-axis tracking structure, which was manually pointed at the sun. The geometrical arrangement of the panel and focal plane was maintained according to the design of the full dome lens. The radiant-flux measurement system consisted of eight independently wired silicon photovoltaic cells mounted in a line on a water-cooled heat sink. The cells were specially designed for concentrated sunlight by Applied Solar Energy Corporation. The linear array of cells was motor-driven to scan the focal plane at the rate of about 1 inch per second.

Prior to each test run, the cells were individually calibrated to determine the proportionality factor between short-circuit current and irradiance. This calibration was done two ways. With the panel covered to prevent focussing onto the cells, the structure was pointed at the sun and

sunlight while allowing direct sunlight to reach the cell. The cell short-circuit current was then divided by a pyrhelimeter direct insolation measurement to obtain the proportionality constant. The second calibration was done with a shading disk over each cell, instead of the collimating cylinder. The difference in cell short-circuit current between fully illuminated (no disk) and shaded (with disk) conditions was divided by the pyrhelimeter direct insolation measurement to obtain the proportionality constant. Both constants agreed with one another for each cell, verifying the calibration.

An actual test run consisted of first measuring the total irradiance on each cell with the panel covered and the structure pointed at the sun. This provided the baseline irradiance on each cell. Next, the panel was uncovered and the cells were driven across the focal plane, while monitoring their short-circuit-current outputs with an eight-channel strip-chart recorder. The measured radiant flux profile minus the baseline irradiance thus provided a two-dimensional flux map for the focal plane. This flux map was then integrated over various size receiver circles to provide the intercepted energy transfer rate. The projected area of the panel times the measured direct insolation provided the incident energy transfer rate. The ratio of intercepted to incident energy transfer rate is the optical efficiency of the panel for each receiver circle, which relates to geometric concentration ratio.

Key results of the testing are presented in Figure 8 and Table 4. Figure 8 shows the intercept factor versus receiver circle radius. Intercept factor is here defined as the optical efficiency for a given receiver radius divided by the optical efficiency for a large receiver radius of 13.66 inches. Table 4 shows the measured versus predicted optical efficiency for various geometric concentration ratios. (For the dome lens, geometric concentration ratio is of course the square of the ratio of lens aperture radius (18 feet) divided by receiver circle radius.) The prototype lens panel had a continuous linear defect covering about 3.7% of its area due to poor lamination of the lensfilm to the acrylic superstrate. This defect was not optically transparent. If the defective area is subtracted from the lens panel area, the corrected efficiency numbers become those shown in the final column of Table 4. Note that for the design concentration ratio of 1500 X, the predicted optical efficiency was 82%, not accounting for absorption or scattering losses. The measured efficiency was 77%, while the corrected measured efficiency was 80%. This close correlation between measured and predicted optical efficiency verifies the following points:

- (1) The dome lens will perform efficiently at high concentration ratios.
- (2) The dome lens can be made as a parquet of linear lens segments.
- (3) The optical effect of manufacturing and alignment errors on dome lens performance is negligible, since these errors were not included in the analytical predictions, while the prototype was crudely assembled and aligned.
- (4) The dome lens optical performance is accurately predicted with a simple dispersive cone optics computer code.

PRACTICAL MASS PRODUCTION OF DOME LENS PANELS

While the method of manufacturing of the prototype panel was labor-intensive, requiring the linear lens segments to be cut into trapezoidal shapes and laminated to a single-piece superstrate, the parquet geometry provided excellent optical performance. If the lens parquet panels could be made without the cutting and integration of the small segments, the dome lens approach would be far more practical. Fortunately, such a practical mass-production approach is now available, as described below.

3M Company, under Sandia National Laboratories - Albuquerque funding, has this year adapted their low-cost, continuous lensfilm process for making prismatic sheet to lens designs without linear prism geometry. 3M has successfully made parquets of annular-prism point-focus lenses by the lensfilm process. This achievement means that the dome lens panels could also be made by the lensfilm process. The lensfilm tooling would include the parquet of linear lens elements in the tooling itself. Thus, the lensfilm produced on the tooling would consist of a continuous strip of acrylic sheet with dozens of panels (like the one shown at the bottom of Figure 4) reproduced one after the other on the strip. These panels could be easily cut out of the strip, since lensfilm is only 0.5 mm thick. The completed panel could be laminated to a thicker superstrate if required; however, with the large error tolerance of the dome lens, it is quite possible that the lensfilm could be used without a superstrate, especially so if the dome interior is slightly pressurized.

REFERENCES

1. O'Neill, M.J., "Solar Concentrator and Energy Collection System," U.S. Patent No. 4,069,812, 24 January 1978.
2. O'Neill, M.J., "A Unique New Fresnel Lens Solar Concentrator," Silver Jubilee Congress of the International Solar Energy Society, Atlanta, Georgia, May 1979.
3. O'Neill, M.J. and R.A. Waller, "Analytical/Experimental Study of the Optical Performance of a Transmittance-Optimized Linear Fresnel Lens Solar Concentrator," Annual Meeting of the International Solar Energy Society, Phoenix, Arizona, June 1980.

FIGURES AND TABLES

Figures and tables are located on the following pages.

POINT FOCUS FRESNEL LENS CONCENTRATOR

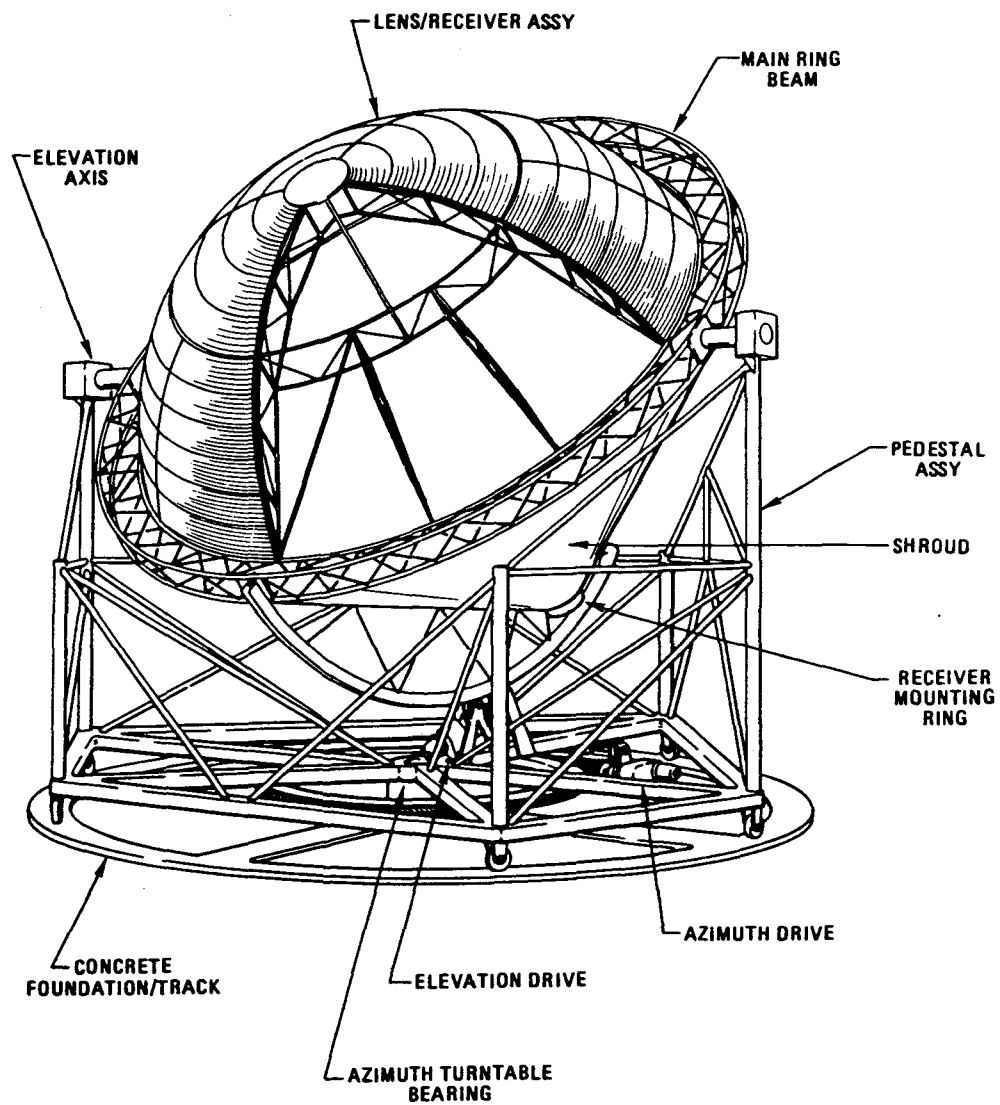


FIGURE 2 -
**PRISM FACE OVER-EXTENSION
 TO MINIMIZE OPTICAL LOSSES**

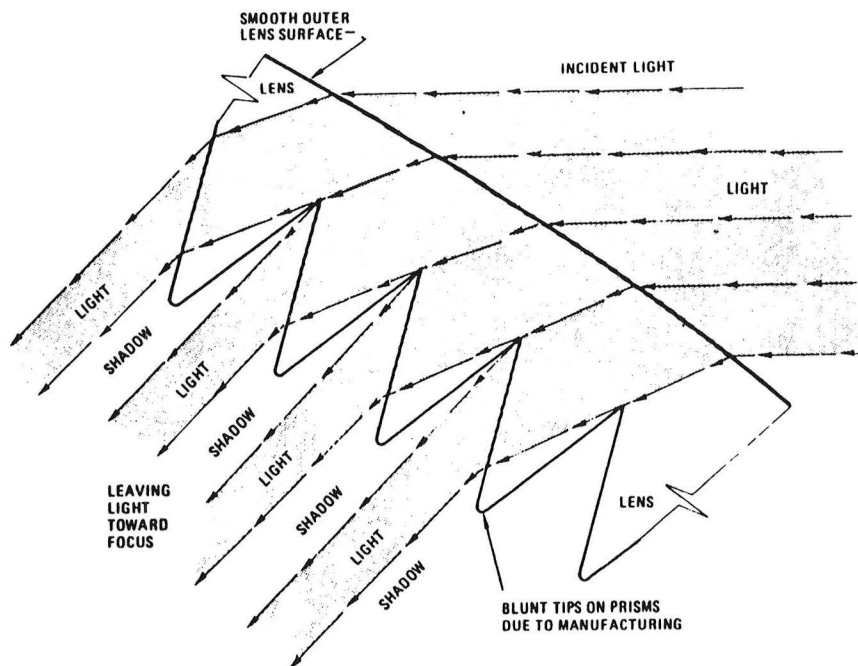
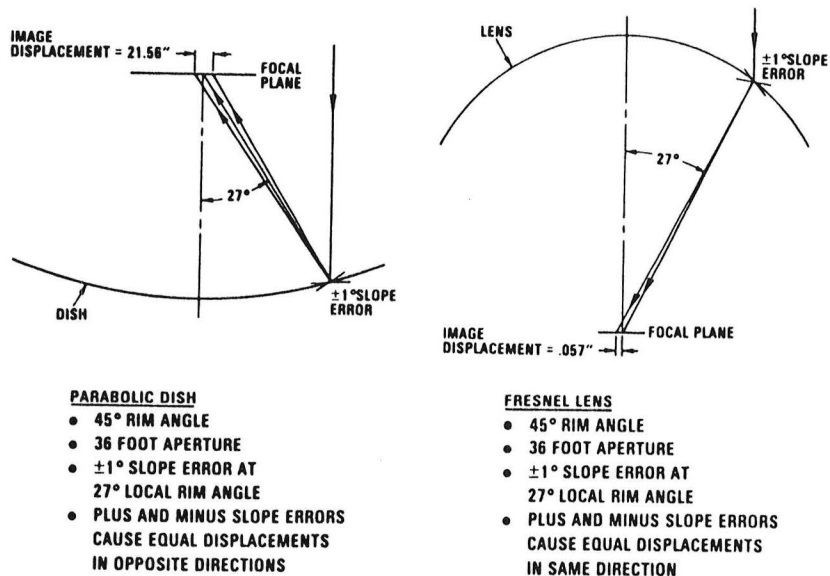


FIGURE 3 - **SLOPE ERROR EFFECT ON IMAGE
 DISPLACEMENT FOR FRESNEL
 CONCENTRATOR vs PARABOLIC DISH**



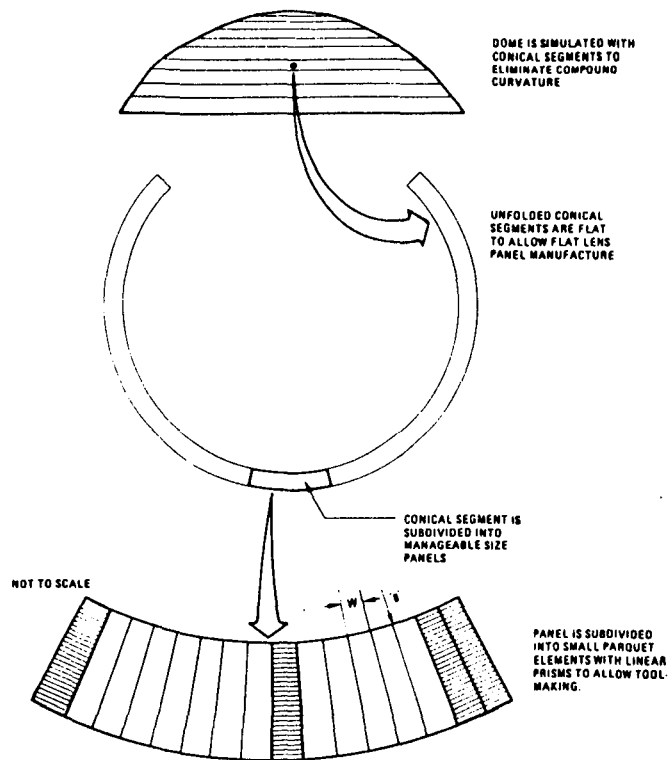


FIGURE 4 - GEOMETRY INVOLVED IN USING FLAT LINEAR FRESNEL LENS ELEMENTS TO MAKE DOME POINT FOCUS LENS

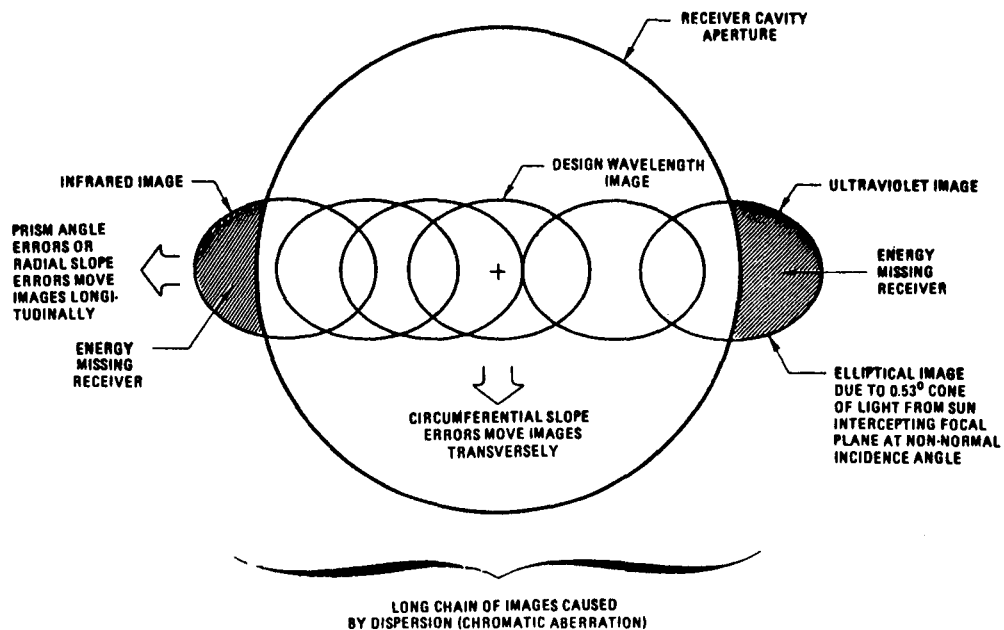


FIGURE 5 - TYPICAL IMAGE PATTERN PRODUCED BY DIFFERENTIAL ELEMENT OF LENS SHOWING EFFECTS OF DISPERSION AND ERRORS - NOT TO SCALE

FIGURE 6 - FLUX PROFILES
FOR OPTIMAL 45°
RIM ANGLE LENSES

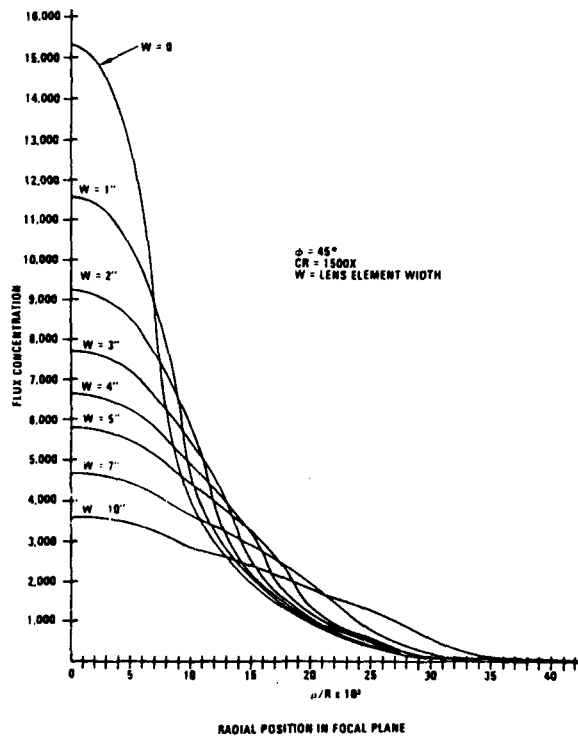


FIGURE 7 - EFFECTIVE TRANSMITTANCE VERSUS
GEOMETRIC CONCENTRATION RATIO
FOR SEGMENTED LENS

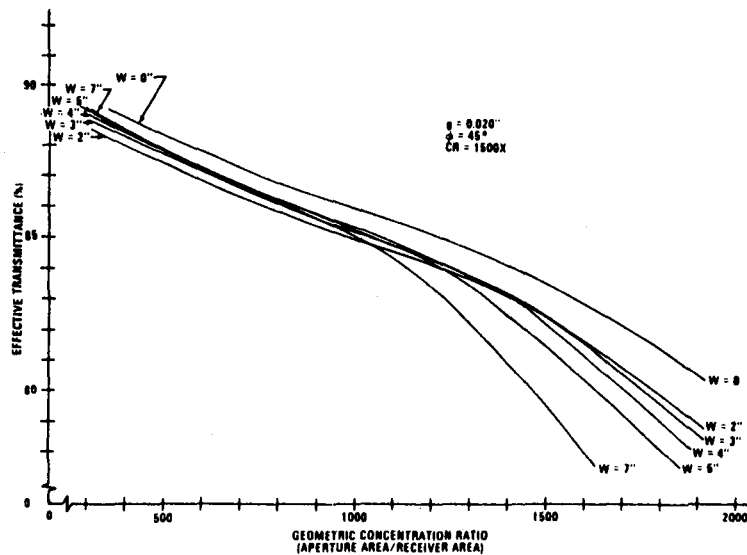


FIGURE 8

ENTECH, INC. POINT-FOCUS LENS PANEL TEST RESULTS - INTERCEPT FACTOR

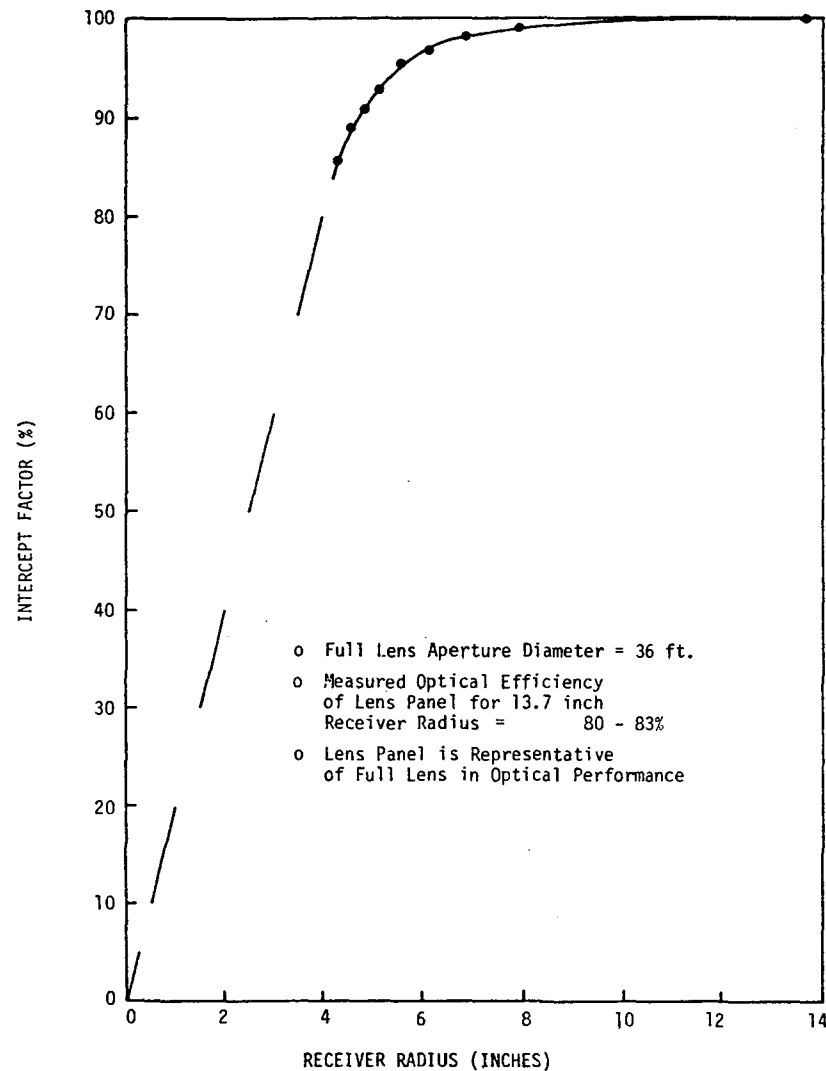


TABLE 1

RECOMMENDED SYSTEM DESCRIPTION

• PHYSICAL	
CONCENTRATOR APERTURE DIAMETER	11M (36 FT.)
CONCENTRATOR RIM ANGLE	45 DEGREES
OVERALL COLLECTOR WEIGHT	13,000 POUNDS (EXCLUSIVE OF RECEIVER)
• LENS PANELS	
REFRACTIVE MATERIAL	ACRYLIC (2.4 MM NOMINAL)
PANEL CONSTRUCTION	BONDED CONICAL SEGMENT PANELS
DUST PROTECTION	PRESSURIZED INTERIOR (BETWEEN LENS AND SHROUD)
• LENS/RECEIVER ASSEMBLY	
LENS SUPPORT STRUCTURE	STRUCTURAL STEEL SPACE FRAME WITH MAIN RING BEAM, 12 RADIAL BEAMS, AND INTERMEDIATE SUPPORTS.
RECEIVER SUPPORT STRUCTURE	BIPOD AND SWAY BRACES, WITH PRESSURIZED SHROUD
• PEDESTAL (ALLOADE)	
AXIS CONFIGURATION	EL OVER AZ WHEEL TRACK
CONSTRUCTION	STRUCTURAL STEEL SPACE FRAME
• FOUNDATION	
TRACK	CIRCULAR REINFORCED CONCRETE RING
AZIMUTH AXIS	CONCRETE PIER FOR AZ BEARING MOUNT. CONCRETE BEAMS INTEGRATING PIER AND RING TOTAL CONCRETE 7CU. YDS.
• DRIVES AND TRACKING	
AZIMUTH RANGE	:180 DEGREES
AZIMUTH DRIVE	CABLE WINCH, POSITIVE ACTION
MAX. AZIMUTH VELOCITY TO STOP	2,000 DEG/HOUR
AZIMUTH MOTOR	AC SYNCHRONOUS STEPPER, 1800 IN-OZ @ 72 RPM
ELEVATION RANGE	:90 DEGREES
ELEVATION DRIVE	CABLE WINCH, POSITIVE ACTION
MAX. ELEVATION VELOCITY TO STOP	2,000 DEG/HOUR
ELEVATION MOTOR	1800 IN-OZ @ 72 RPM, AC SYNCHRONOUS STEPPER
• RECEIVER	
WEIGHT (JPL DEFINED)	705 POUNDS

TABLE 2

SYSTEM PERFORMANCE SUMMARY

• OPTICAL PERFORMANCE	CASE I	CASE II
GEOMETRIC CONCENTRATION RATIO	1500	500
LENS TRANSMITTANCE	90%	90%
RECEIVER INTERCEPT FACTOR	92%	99%
BLOCKING/SHADING FACTOR	94%	94%
OVERALL OPTICAL EFFICIENCY	78%	83%
• THERMAL PERFORMANCE (@ 800 WATTS/M² INSOLATION)		
RECEIVER CAVITY TEMP	815 °C (1500 °F)	371 °C (700 °F)
RECEIVER RADIATION THERMAL LOSS	5 KW (THERMAL)	2KW (THERMAL)
COLLECTOR NET OUTPUT	54 KW (THERMAL)	61 KW (THERMAL)
COLLECTOR OVERALL EFFICIENCY	71%	80%

TABLE 3

PROTOTYPE LENS PANEL

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LOCATION WITHIN DOME LENS - CONICAL SEGMENT BOUNDED BY LOCAL RIM ANGLES OF 27.9° AND 32.1°.

- PANEL SIZE - 4 FEET AVERAGE CIRCUMFERENTIAL ARC LENGTH BY 2 FEET STRAIGHT LENGTH.
- CONFIGURATION - 12 LINEAR PRISMATIC ELEMENTS, 4 INCH AVERAGE WIDTH BY 2 FEET LENGTH.
- MATERIALS - LINEAR PRISMATIC ELEMENTS MADE OF 3M ACRYLIC LENS-FILM. SOLVENT-BONDED TO SINGLE PIECE OF EXTRUDED ACRYLIC SHEET - TOTAL PANEL THICKNESS = 0.1 INCH.

TABLE 4

PREDICTED VERSUS MEASURED DOME LENS OPTICAL EFFICIENCY

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<u>GEOMETRIC CONCENTRATION RATIO</u>	<u>PREDICTED OPTICAL EFFICIENCY</u>	<u>MEASURED OPTICAL EFFICIENCY</u>	<u>CORRECTED* MEASURED OPTICAL EFFICIENCY</u>
1000 X	85%	79%	82%
1250 X	84%	78%	81%
1500 X	82%	77%	80%
1750 X	80%	75%	78%
2000 X	77%	74%	77%

* CORRECTING FOR A 3.7% NON-TRANSPARENT DEFECTIVE AREA ON THE PROTOTYPE LENS PANEL.